Effects of simulated acidic, metal-containing precipitation on coniferous litter decomposition[1]

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Depths of undegraded litter in hardwood and boreal forest ecosystems of Camels Hump Mountain in the Green Mountains of Vermont doubled between 1965 and 1982. Simulations of litter leaching by acidic and nonacidic snowmelt, fog water, or rain showed that hydrogen ions were retained by coniferous-needle litter and both cations and anions were leached. *In vitro* studies on litter degradation showed that acidic conditions reduced microbial CO_2 evolution from litter. CO_2 evolution was further repressed by the presence of Pb and Zn, but not by Al or Cu. Cellulose breakdown was unaffected in acidic, metal-containing soils treated with water acidified to pH 3.8. Reduction in litter decomposition, which could adversely alter the rates of mineral cycling in natural ecosystems, may be due to repression of the metabolism of litter-degrading microflora by precipitation acidity and metals present in soils and introduced by polluted rain.

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L'épaisseur de la litière non-dégradée a doublé entre 1965 et 1982 dans les écosystèmes des forêts de bois francs et des forêts boréales du mont Camels Hump, dans les Montagnes Vertes du Vermont. Des simulations du lessivage de la litière par de l'eau de fonte de neige, de l'eau de brouillard et de la pluie, aussi bien acides que non-acides, montrent que les ions hydrogène sont retenus par la litière de feuilles de conifères, mais que les cations et les anions sont lessivés. Des études *in vitro* de la dégradation de la litière montrent que l'acidité diminue l'évolution microbienne du CO_2 à partir de la litière. L'évolution du CO_2 est également diminuée par la présente du Pb et Zn, mais non par Al ou Cu. La dégradation de la cellulose n'est pas effectuée dans les sols acides contenant des métaux et traités par de l'eau acidifiée jusqu'à un pH de 3,8. La diminution de la décomposition de la litière, qui pourrait modifier de manière dommageable les taux de recyclage des éléments minéraux dans les écosystèmes naturels, pourrait être due à la répression du métabolisme de la microflore responsable de la dégradation de la litière, cette répression étant causée par l'acidité de la précipitation et par les métaux lourds introduits dans les sols par la pluie polluée.

[Traduit par le journal]

Introduction

The role of litter of forested ecosystems in nutrient cycling (Dickinson and Pugh 1974), humus formation (Ivarson and Sowden 1959), water balance (Swift et al. 1979), and as a habitat for litter-comminuting fauna (Ghilarov 1971) is important in the study of ecosystems (Olson 1972). In boreal ecosystems, a significant fraction of required plant nutrients is tied up in litter (Millar 1974), and even under optimum conditions, litter degradation is slow. Perturbations of degradation processes may have serious consequences for ecosystem stability.

We report here that litter depth on the forest floor of ecosystems of Camels Hump Mountain in the Green Mountains of Vermont has increased significantly between 1965 and 1982. In addition, the average percentage of organic matter in the top 5 cm of boreal-forest soil increased. The precipitation reaching the northeastern U.S.A., and adjacent Canadian provinces is acidic and contains metal ions (Galloway et al. 1980) that accumulate in soils (Reiners et al. 1975; R. M. Klein, unpublished). In assessing the possible effects of acid rain on forested ecosystems, one question is whether acidic, metal-containing precipitation is affecting leaching of litter, litter degradation, and consequently, mineral cycling in these forests. The purpose of this study was to make field determinations of litter depth followed by laboratory simulation experiments to assess this possibility.

Materials and methods

Field studies

Measurements of litter depth in 1965 (Siccama 1967) were made by scaling litter depth on the sides of soil pits dug at each of the 11 elevations on Camels Hump Mountain (latitude 44°19′; longitude 72°53′). The 1982 data were collected by scaling litter depths without digging soil pits. In both studies, litter depth included only those accumulations in which litter was visually recognizable as plant parts (leaves, needles, twigs); care was taken to distinguish between morphologically intact litter and organic debris in which leaf or needle structure

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had been degraded. Organic matter in the upper 5 cm of soil (02/Al) plus the F and H layers was determined by loss on ignition.

Laboratory studies

Litter was obtained by cutting live branches of balsam fir (*Abies balsamea* (L.) Mill.) and red spruce (*Picea rubens* Sarg.) in the autumn from trees growing at low-elevation rural sites in northern Vermont, air drying the branches, and collecting the needles. Fir and spruce needles were mixed in a 2:1 ratio to approximate the proportions in coniferous litter of a mature New England fir–spruce association. The mixtures were stored in plastic bags at room temperature. Simulated acidic precipitation was made with glass-distilled water containing H_2SO_4 and HNO_3 in a 60:40 mequiv. H^+ ratio (cf. Anonymous 1980) and were adjusted to desired pH values.

Leaching of ions from litter into ground water may result in their loss from the ecosystem and may reduce the mineral supply available to decomposer organisms. Two modes of leaching from litter can be visualized: leaching via snowmelt and from precipitation (fog, drizzle, or heavy rain). As snow melts, litter may be flooded with pools of very acid water during the warmer parts of a day (Johannessen and Henrickson 1979). In our simulation, 10 g of needle litter in polypropylene flasks was placed in contact with 70 mL of acidified water. Flasks were incubated at 3.5°C (Witkamp and Ausmus 1976) for at least 3 h on a rotary shaker at 175 cycles per minute. Leachate was collected at intervals, strained, centrifuged at 4500 *g*, and filtered. To simulate snowmelt percolation, disks of 200 mL of acidified water were frozen at −5°C and placed on top of 10 g of needle litter in plastic Buchner funnels at either 5 or 15°C and the equivalent of ca. 2 cm of percolate was collected. About 10 days were needed to collect percolate at 5°C and 8 h were needed to collect percolate at 15°C.

Litter is also leached (*i*) by condensing fog droplets (0.05–0.15 mm in diameter), (*ii*) by drizzle (0.15–0.5 mm in diameter), and (*iii*) by raindrops (0.5–4.0 mm in diameter) (Day and Sternes 1970). These were all produced by calibrated dispersion nozzles (Bete Fog Nozzle Inc., Greenfield, MA, U.S.A. 01302) from simulated precipitation water contained in pressurized tanks (courtesy Burlington Coca-Cola Co.) in precipitation chambers (Scherbatskoy, unpublished). For each tested precipitation pH and droplet size range, four plastic Buchner funnels fittted with rubber stoppers were inserted into plastic flasks and placed on a motorized turntable (1 r/min) to ensure uniform reception of precipitation. Funnels were charged with 10 g of needle litter and a single 2-cm rain equivalent was colleted. Variations in volume were ca. 10% about the mean. Time of collection varied; fog required ca. 100 min, drizzle required 35 min, and rain required 6 min.

Leachates were analyzed for pH, conductivity at 25°C, K^+ and Ca^{+2} (flame photometry), and PO_4^{-3} (Rand et al. 1975).

Litter metabolism

Studies on microbial decomposition of litter utilized the respiratory method of Rühling and Tyler (1973) which accurately reflects the metabolic activity of microflora involved in decomposition (Bunnell et al. 1977). Acidified water was enriched with metal ions (all as chlorides) in cation concentrations calculated (cf. Lindsay 1979) on the basis of our analyses for metals in boreal soils of Camels Hump. Metal concentrations approximated 200 mg/L Al, 15 mg/L Cu, 200 mg/L Pb, and 90 mg/L Zn (F. Reed and R. M. Klein, unpublished). Fifteen grams of needle litter were placed in polypropylene bottles together with 30 mL of acidified water containing metal ions. The bottles were sealed tightly and shaken to wet the needles (Rühling and Tyler 1973). The bottles were incubated for 4 days at 20°C. Lids were removed once a day for 1 h to provide adequate aeration. On day 5, the bottles were flushed with compressed air to displace accumulated CO_2. Five millilitres of 1.00 *N* NaOH in plastic vials was inserted into each bottle, which was recapped and incubated at 20°C for 7 h. The vials were removed and 2.0 mL of 1.00 *N* $BaCl_2$ was added. The vial contents were titrated to a phenolphthalene end point with 0.250 *N* HCl. Milligrams of CO_2 produced by microbial metabolism per gram dry weight litter per hour was calculated; appropriate control and titration blanks were included. A separate study using metals in combination was also performed.

Cellulose decomposition

Although microbial metabolism measures early stages in litter decomposition, dissolution of cellulose is a slower process, requiring months or years (Mikola 1955). To obtain information on cellulose decomposition, a simulation using strips of heavy cotton-duck cloth was employed (Schmidt and Ruschmeyer 1958*a*, 1958*b*). The starch sizing was removed by soaking the cloth in warm water and 38 × 150 mm strips were buried in soils obtained from three elevations representing a hardwood zone at 550 m, a transition zone at 780 m, and a boreal zone at 985 m. The soils were characterized for pH and metal concentrations, placed in plastic trays with adequate drainage and the cotton strips were buried 3 cm below the soil surface. The trays were incubated in darkness at 22–23°C with soils kept at near field capacity (cf. Siu 1951) by spraying at 2- to 3-day intervals with acidified water at pH 3.8. The tensile strength of the strips was determined with a Scott model J2 tester (courtesy Professor Charles Noel, Clothing, Textile, and Design Program, University of Vermont, VT).

Results

Field studies

Over the 1965–1982 study period, litter depth in the three major ecosystem zones on Camels Hump increased by a factor of ca. 2 (Table 1). The organic-matter component of the 02/Al horizon also increased significantly (Table 1).

Laboratory studies

Except at an initial pH of 5, mixed fir–spruce litter sorbed H^+, with more uptake at pH 3 than at pH 4. There was little net change at pH 5 (Fig. 1). The amount of H^+ sorbed was the same as that taken up when litter was in contact with "pools" of water, the simulation of liquid snowmelt. Uptake occurred quickly, with steady-state conditions being reached within the 1st h of water–litter contact.

The release of all ions (measured as total conductivity) was most pronounced when litter was in contact with pools of water (Fig. 2). In contrast with H^+ uptake,

TABLE 1. Changes in litter depth between 1965 and 1982 and changes in percentage organic matter in the 02/Al horizon between 1965 and 1979 in ecological zones of Camels Hump Mountain in the Green Mountains of Vermont

Zone and elevation	Litter depth (cm)			% organic matter		
	1965*	1982	1982 as % of 1965	1965*	1979**	1979 as % of 1965
Hardwood (550–730 m)	3.5±0.45† (n = 12)	7.3±1.5 (n = 12)	210	35.2	53.8	153
Transition (730–850 m)	3.8±0.45 (n = 6)	7.1±1.7 (n = 27)	180	51.8	94.2	182
Boreal (850–3800 m)	4.5±1.7 (n = 12)	7.8±1.7 (n = 54)	170	62.8	99.5	161

*Siccama (1967).
**Unpublished data courtesy of Dr. Thomas Siccama.
†± standard deviation.

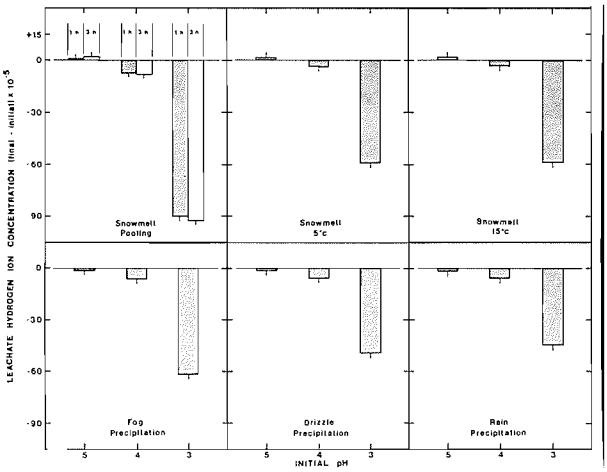

FIG. 1. Hydrogen-ion concentrations in leachates of fir–spruce needle litter exposed to simulated acid precipitation initially at pH 3, 4, or 5. Litter treated with H_2SO_4–HNO_3 simulated acidic precipitation at given initial pH values, and final pH determined at end of experiment. Results calculated as final H^+ concentration–initial H^+ concentration to determine whether H^+ was sorbed or released from litter during test period. Experimental details in Materials and methods section.

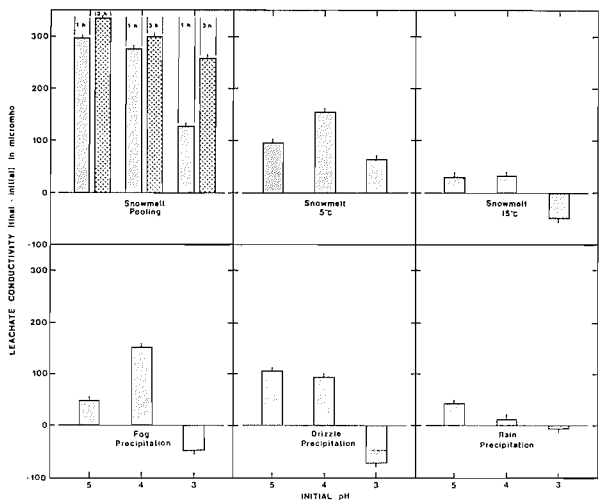

FIG. 2. Total conductivity in leachates of fir–spruce needle litter exposed to simulated acid precipitation initially at pH 3, 4, or 5. Initial conductivity was 4 μmho (1 mho = 1S) at pH 5; 28 μmho at pH 4 and 228 μmho at pH 3. Experimental details in Materials and methods section.

total ion efflux continued after the 1st h of contact, albeit at a slower rate, through the 3rd h.

Potassium usually dominated the ion efflux (Fig. 3). The pattern of K^+ and the pattern of conductivity efflux for various pH values and for the various modes of leaching were similar at pH 4 and pH 5. There was no obvious similarity of pattern between H^+ and ion efflux, suggesting that ion efflux may not be due exclusively to cation exchange.

Litter metabolism

Wetting needle litter with acidified water at pH values of 3 or 4, which bracket the pH of forest soils of the Camels Hump boreal forest and are in the range of present pH values for snowmelt and precipitation, repressed microbial respiration. Carbon dioxide production at pH 5 was greater than at pH 3 or 4 (Table 2). Aluminum and copper ions presented at low concentrations did not alter respiratory metabolism, while both Pb and Zn at concentrations found in soil repressed CO_2 production as a function of both ion concentration and initial pH. When all four metal ions were provided simultaneously at pH 3, the respiratory repression was smaller than when either Pb or Zn was presented alone.

Cellulose decomposition

Reductions in tensile strength of cotton-duck strips

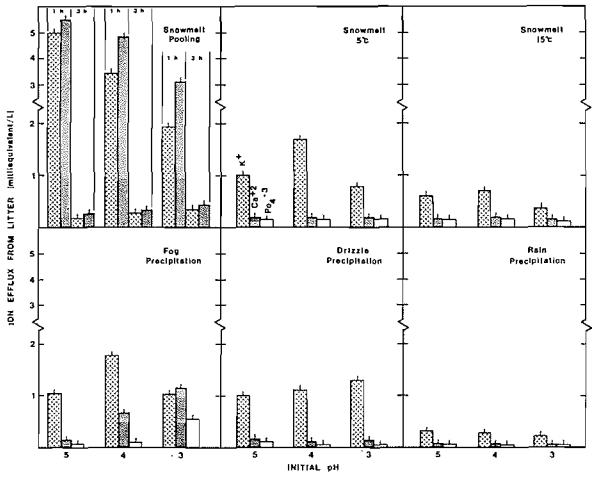

FIG. 3. Concentrations of K^+, Ca^{+2}, and PO_4^{-3} in leachates of fir–spruce needle litter exposed to simulated acid precipitation initially at pH 3, 4, or 5. Experimental details in Materials and methods section.

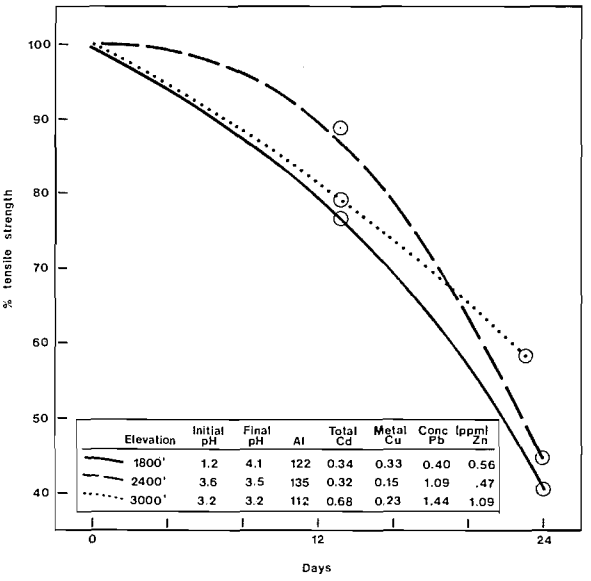

FIG. 4. Reductions in tensile strength of cotton-duck cloth strips buried in soils from hardwood, transition, or boreal mountainous ecosystems. The inserted table presents pertinent soil analyses for pH and total metal concentrations.

buried in soil having different pH values and concentrations of Cd, Pb, and Zn, but comparable levels of Al and Cu, were not significantly different (Fig. 4). Maintaining soil moisture with acidified water did not alter the pH of the soils.

Discussion

Our study attempted to provide laboratory-generated information capable of addressing the potential role of acid precipitation and metals on litter decomposition and

TABLE 2. Effects of pH and metal ions on respiratory activity of fir–spruce needle litter decomposition. Each datum value is an average of four replicates

Initial pH	Metal ions	mg/L	Average mg CO_2/g dry weight litter/h	% of control
Metal ions supplied individually in test solutions				
3.0	—	0	0.70	100
	Al	10	0.80	101
	Al	100	0.87	111
	Cu	5	0.75	95
	Cu	10	0.88	112
	Pb	5	0.55	70*
	Pb	10	0.33	43**
	Zn	5	0.54	69*
	Zn	10	0.53	68*
4.0	—	0	0.74	100
	Al	10	0.88	113
	Al	100	0.92	124
	Cu	5	0.92	124
	Cu	10	0.78	106
	Pb	5	0.71	96
	Pb	10	0.47	63*
	Zn	5	0.78	106
	Zn	10	0.78	106
5.0	—	0	1.13	100
	Al	10	0.88	87
	Al	100	1.06	94
	Cu	5	1.16	103
	Cu	10	1.02	90
	Pb	5	0.98	87
	Pb	10	0.70	63*
	Zn	5	0.96	85
	Zn	10	1.07	95
Metal ions supplied simultaneously in test solutions				
3.0	—	0	1.83	100
	Al	10		
	Cu	5		
	Pb	5		
	Zn	5	1.68	90***

*p = 0.07–0.08.
**p = 0.05–0.04.
***p = 0.10–0.12.

the accumulation of soil organic matter in a New England boreal forest where both have increased over a period of 14 years. Simulation studies cannot, of themselves, prove unequivocally that any single alteration in the environment caused the observed changes; they can only demonstrate that tested factors are potentially capable of accounting for the field observations. However, in view of the quantitative decline in coniferous trees in the boreal forest (Siccama et al. 1982), the observed increase in litter depth cannot be due to cyclic increases in the amount of litter produced by coniferous trees.

The leaching of K^+ and Ca^{+2}, the large increase in total conductivity in litter leachates as a function of

initial pH, and the sorption of H^+ by litter may be contributing factors to reductions in nutrients that may depress microbial activity (Cronan et al. 1978). Fairfax and Lepp (1976) and Lousier and Parkinson (1978) implicated sorption and leaching, particularly from highly acidic, early-spring snowmelt, in elution of both cations and anions and thus nutrient loss.

Effects of metals on microbial decomposition of litter have been examined primarily in areas subjected to massive metal and acid pollution from smelting and refining industries. The accumulation in soils of metals borne by acidic precipitations and their solubilization has been documented (Reiners et al. 1975; Siccama et al. 1980; R. M. Klein unpublished). While the levels of insoluble metal complexes in soils and dissolved metal ions of Camels Hump mountainous ecosystems are at least one order of magnitude lower than those measured near smelters, they are above our 1965 base line (Siccama 1967) and, as shown here, are capable of reducing the metabolism of litter microflora, particularly when metal ions accompany acidic conditions. Rühling and Tyler (1973), Freedman and Hutchinson (1978), and Hutchinson (1979) documented increases in litter depths and organic matter on soils contaminated by industrial acids and metals. Under laboratory conditions, Buchauer (1973) and Bond et al. (1976) found that cadmium or zinc inhibited respiration in litter and Tyler (1974) found that copper and zinc also repressed litter microorganisms. Our findings are also consistent with those of Ebregt and Boldewijn (1977), Freedman and Hutchinson (1978), and Bryant et al. (1979) who also reported suppression of litter degradation by metal ions. Independent of metal pollutants, pH values of 3 and 4 (values which were found in soils and in lysimeter collections of Camels Hump (Reed, unpublished)) suppress litter-degrading microflora (White et al. 1949; Hovland 1981). Reductions in litter respiration could, over a 17-year period, account for the measured increase in litter depth with concomitant alterations in mineral cycling.

The slow process of dissolution and microbial utilization of cellulose, with consequent decrease in the C:N ratio of litter changing to humus, may or may not be affected by acid–metal pollution. Melin (1930) found an inverse relationship between litter acidity and the rapidity of decomposition of mixed coniferous–deciduous litter. Francis et al. (1980) reported that oak-leaf litter breakdown was reduced by 50% when the pH was lowered from 4.6 to 3.5 and Bååth et al. (1980) obtained similar results with *Pinus sylvestris* litter. Our short-term simulation studies and those of Waksman and Heukelekain (1924), Abrahamsen et al. (1980), and Roberts et al. (1980) failed to find alterations in rates of cellulose degradation at acidic pH values. Thus, our finding of an accumulation of organic matter in the 02/Al horizon is currently without experimental explanation.

Studies on litter-comminuting fauna are also important in assessing the causal complex involved in litter degradation (Fenchel and Harrison 1976; Edwards et al. 1970). Hagvar and Abrahamsen (1980) and Stachurska-Hagen (1980) reported that the numbers of these organisms (springtails, mites, etc.) are reduced when forested areas are subjected to acidic precipitation. This aspect of our study is in progress, using a data base for Camels Hump developed in the early 1970's.

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